# REBCO and BSCCO fast neutron irradiations at the LBNL 88-Inch Cyclotron

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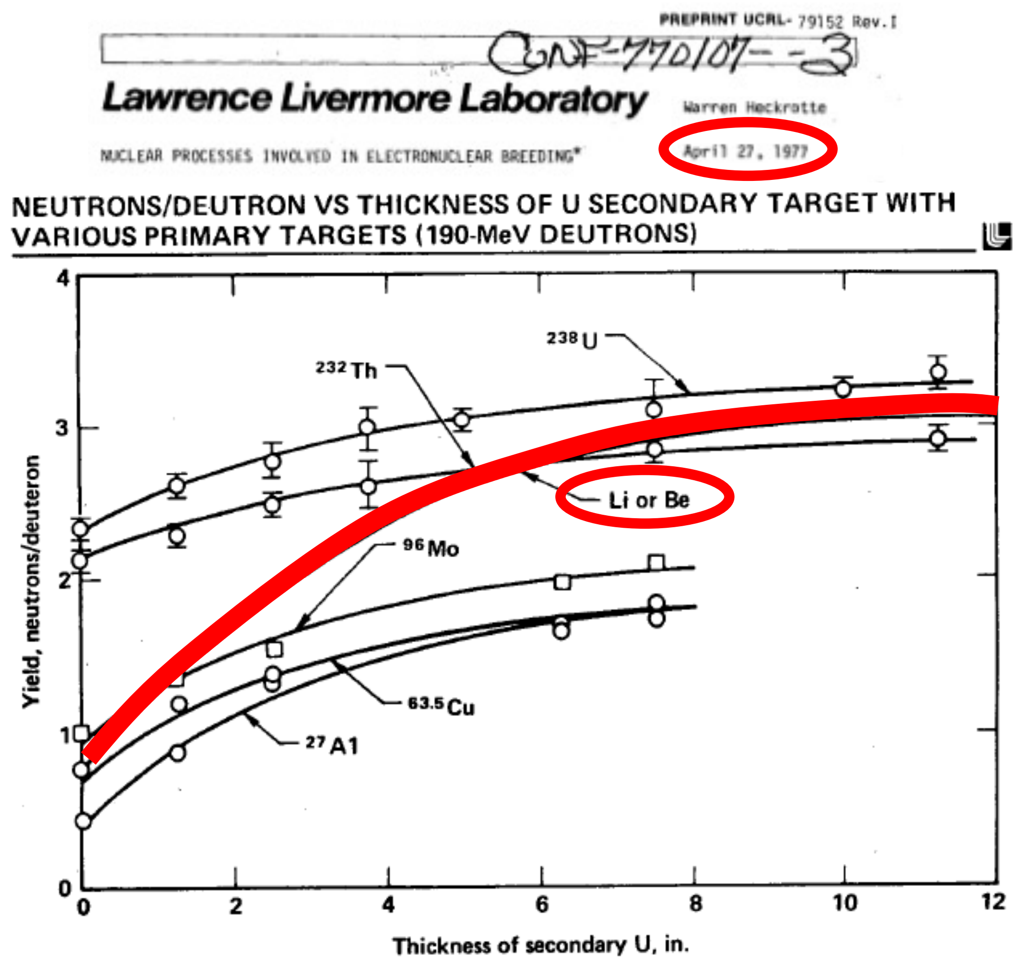
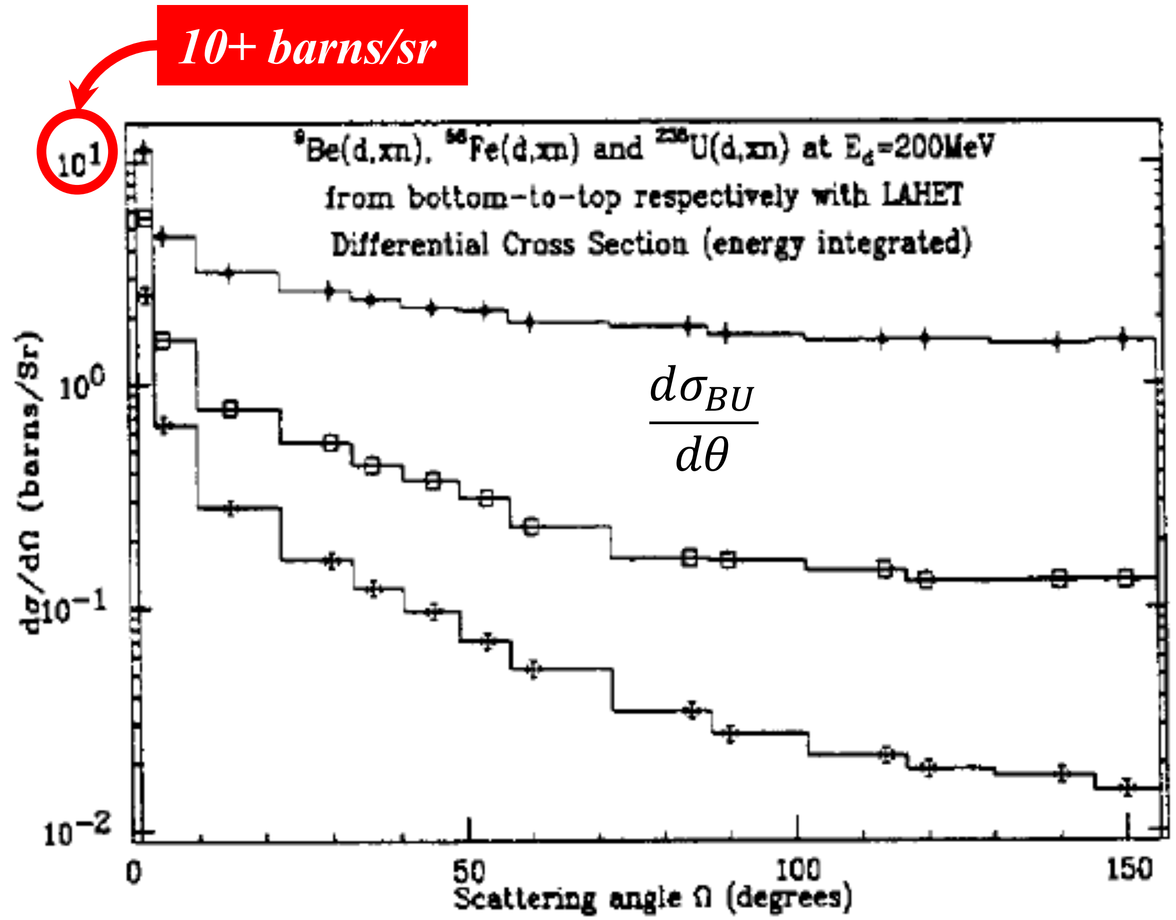
# Thick target deuteron breakup has been known as an effective source of fast, forward focused neutrons and was even considered for $^{239}$Pu production in the 1940s*




*Low-Z targets are particularly good since they have the lowest dE/dx and therefore the longest effective target thickness*




*Thick target deuteron breakup (TTDB) neutron beams on light targets are also strongly forward focused (the neutrons follow the direction of the deuteron beam)*

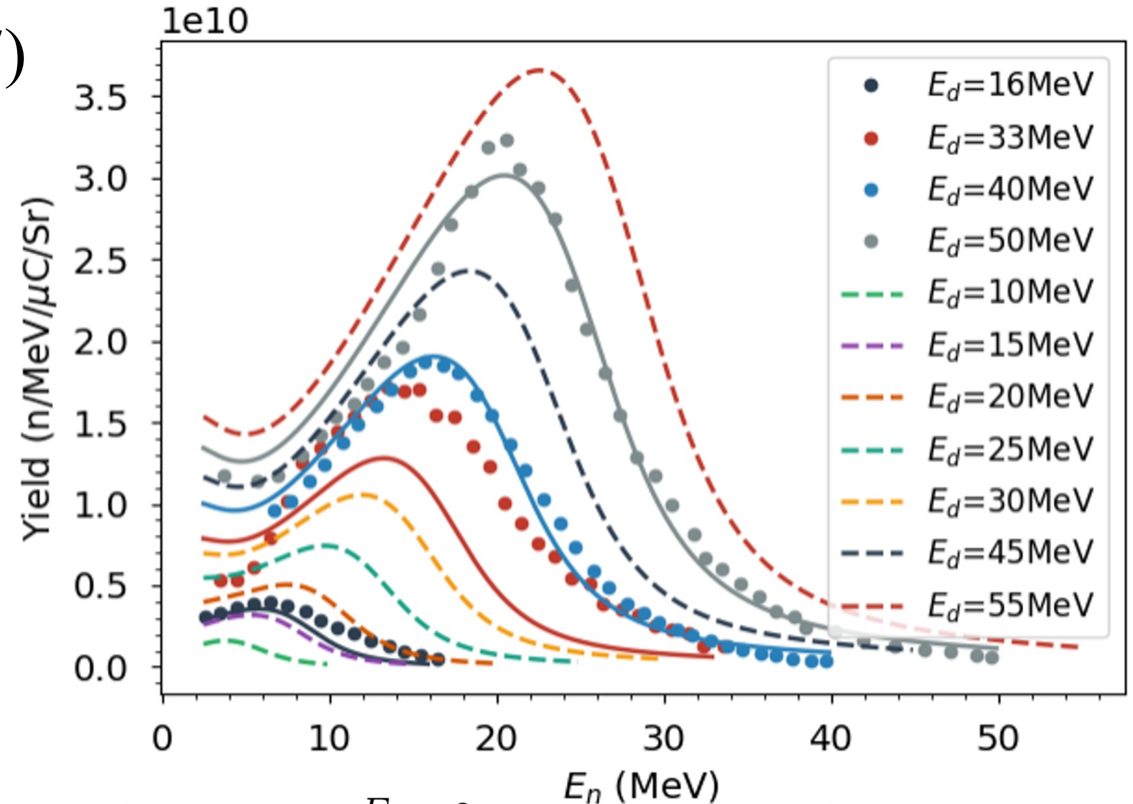


*Thanks to Ian Thompson (LLNL)*

# Jon Morrell* developed a combined 5 parameter model that describes the double-differential TTDB neutron production cross section

- P($E_n$, $\theta$) from R. Serber[1] (Phys. Rev. 72, 11 (1947)
- Pre-equilibrium cross section from Kalbach[2]
- Talys Maxwell-Boltzmann evaporation
- One flat background parameter
- Slowing ($d\varepsilon_d/dx$) from SRIM
- Fit yields to measurements and literature data[3,4]


[1]R. Serber, Phys. Rev 72, 11 (1947)
[2]C. Kalbach Phys. Rev. C 95, 014606 (2017).
[3]Meulders (1975) - 16, 33, 50 MeV
[4]Saltmarsh (1977) - 40 MeV


$$\frac{d^2\sigma(\epsilon_d)}{d\Omega dE_n} = \sigma_{BU}(\epsilon_d) P(E_n) P(\theta)$$

1 parameter each

Shape & Magnitude

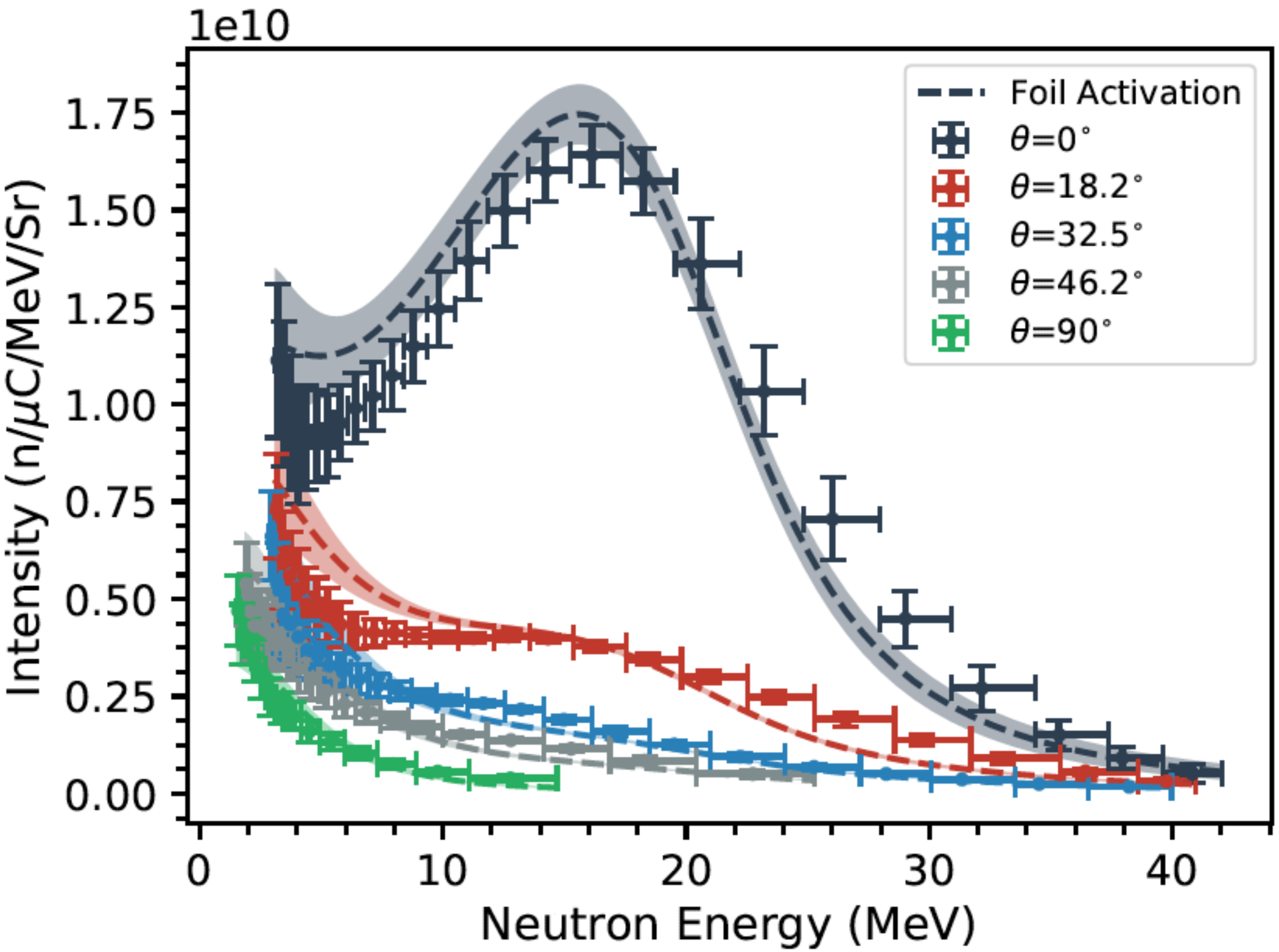
$$Y(E_n, E_d, \hat{\Omega}) = n \int_{\hat{\Omega}} \int_0^{E_d} \frac{d^2\sigma(\epsilon_d)}{d\Omega dE_n} \left(\frac{d\epsilon_d}{dx}\right)^{-1} d\epsilon_d d\Omega$$

Our Results were just published: J.T. Morrell *et al.,* Phys. Rev. C 108, 024616 (2023).
https://doi.org/10.1103/PhysRevC.108.024616


Jon Morrell


*UCB Ph.D. 2021, now at LANL

# We benchmarked the model for 40 MeV deuterons on a thick Be breakup target




**40 MeV deuterons***

*$\phi$=1.4x10$^{11}$ n/s/cm$^2$ @ 1 cm*
*$\phi$=2.0x10$^{10}$ n/s/cm$^2$ @ 10 cm*
*$\phi$=2.2x10$^5$ n/s/cm$^2$ @ 10 m*

**50 MeV deuterons***

*$\phi$=7.5x10$^{12}$ n/s/cm$^2$ @ 1 cm*
*$\phi$=1.2x10$^{11}$ n/s/cm$^2$ @ 10 cm*
*$\phi$=6.7x10$^5$ n/s/cm$^2$ @ 10 m*

***Spectral variation as a function of angle allows for simultaneous measurements***



*Assumes 20 μA beam and 0°

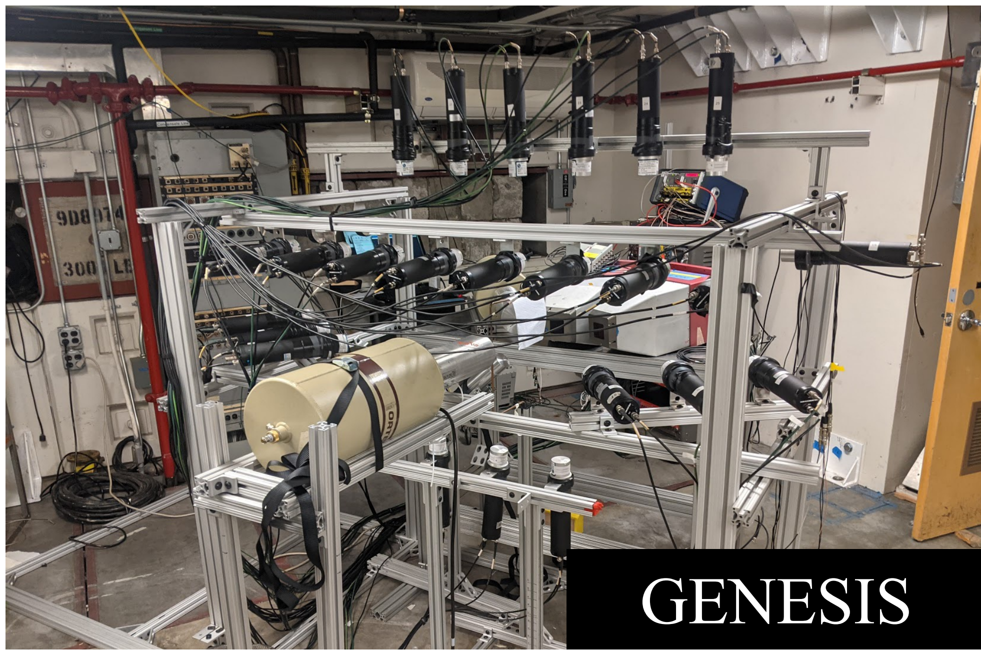
# TTDB neutron beams are available at two caves at the 88-Inch cyclotron*

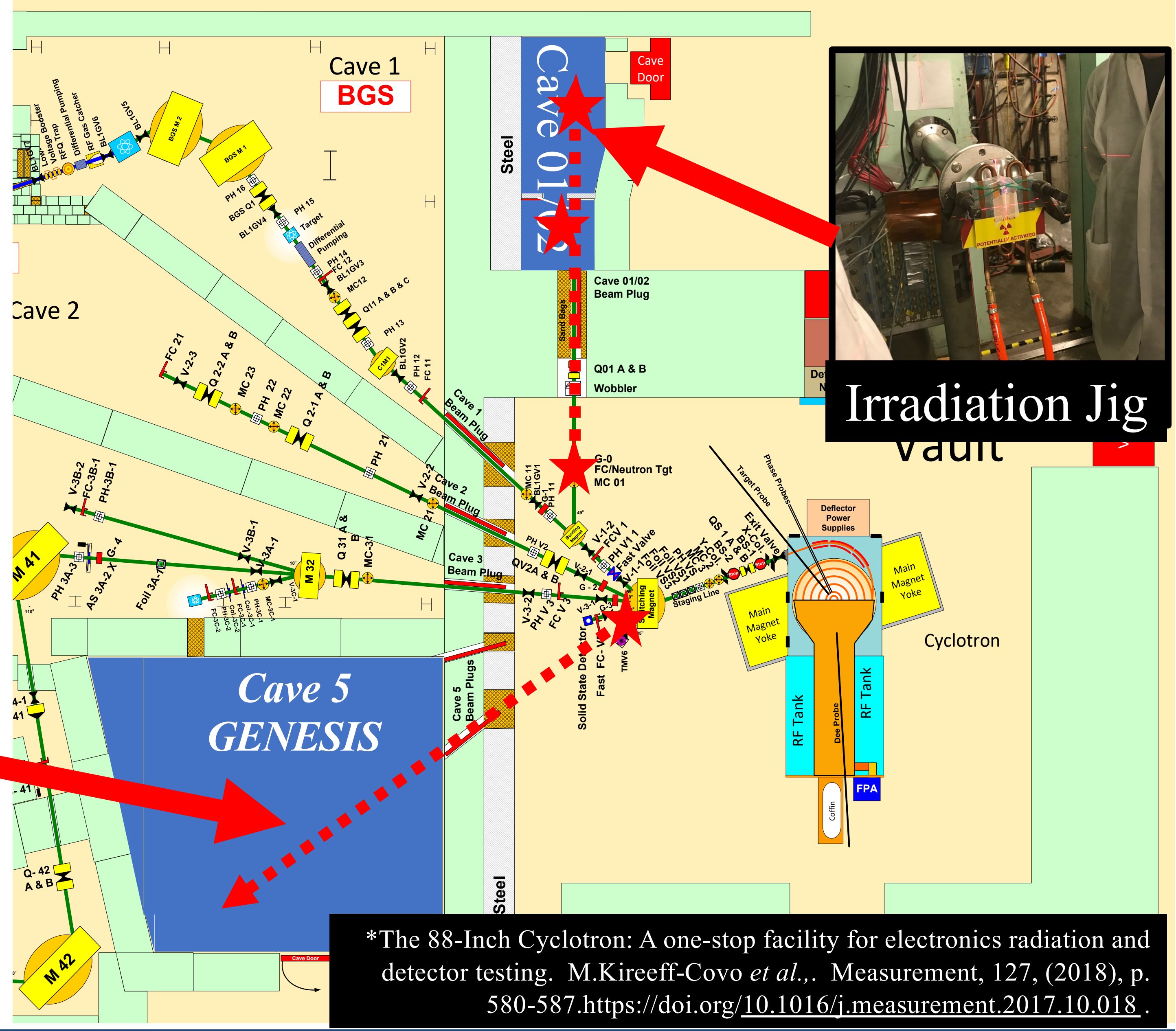
**<u>Cave 0 (This talk)</u>**

- High-level cave capable of running up to 1.5 kW of beam power (ASE limit).
- Breakup in Vault or Cave.
- Max flux : $10^{12}$ n/s/cm$^2$

**<u>Cave 5 (See J.A. Brown's talk)</u>**

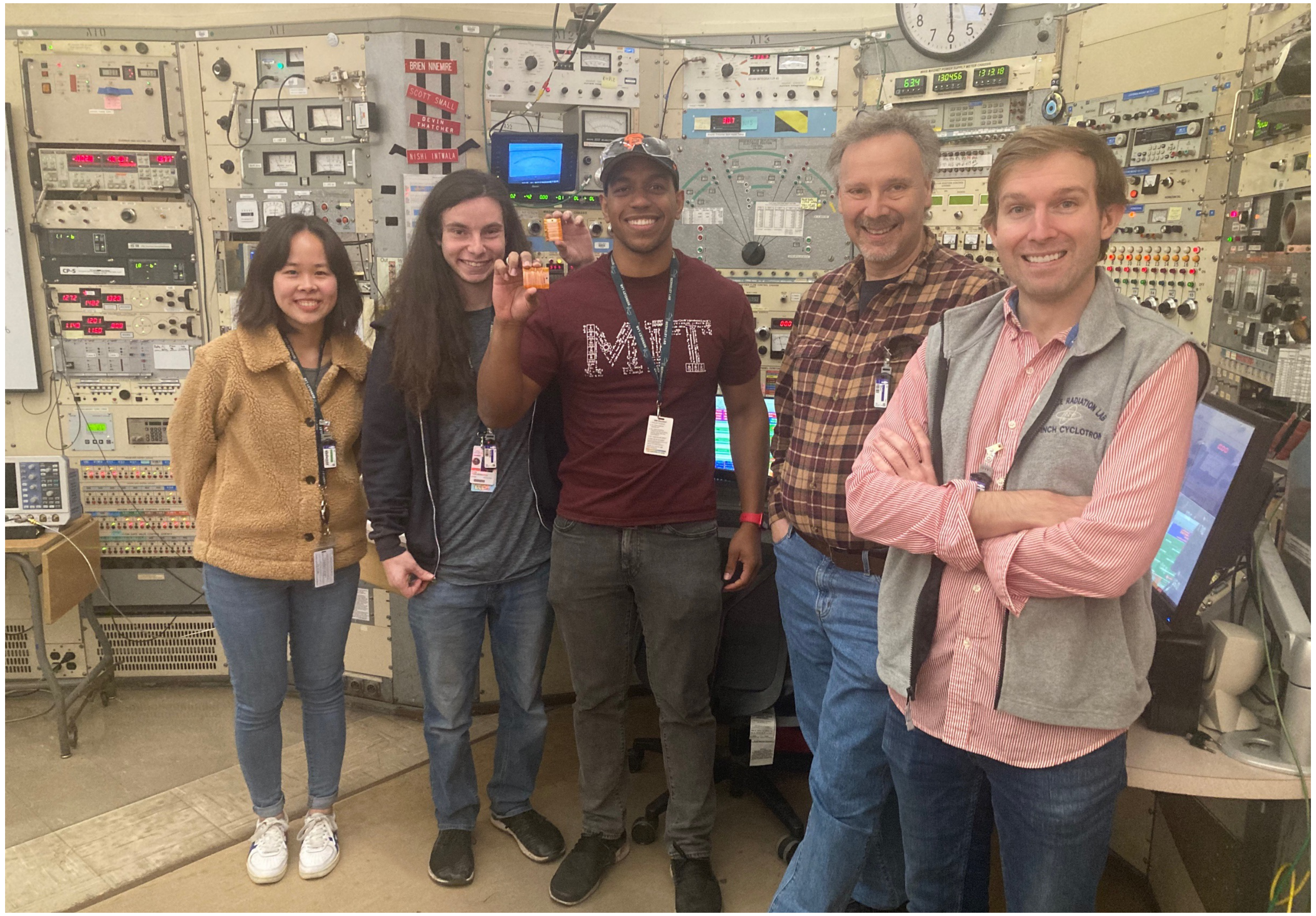
- "TOF Quality" flight path from 7-22 m.



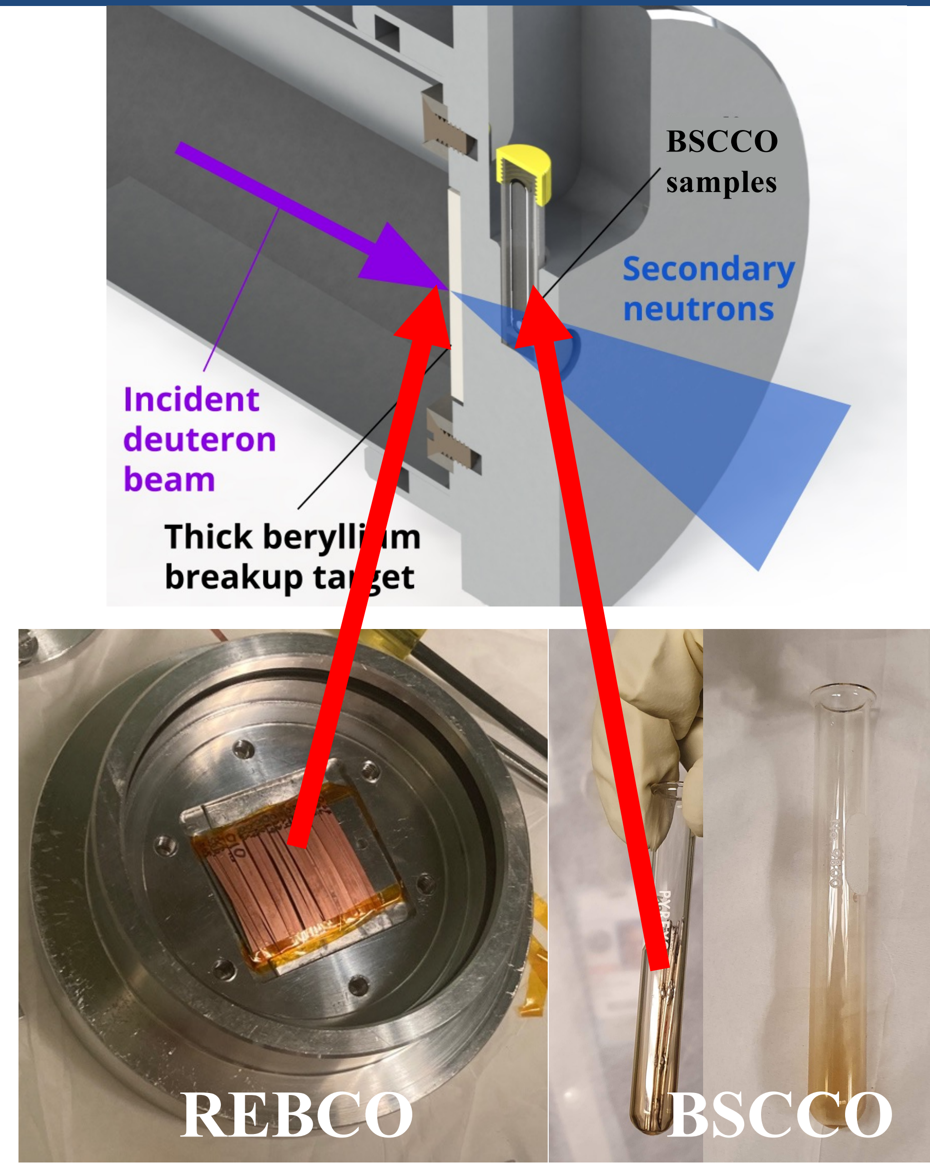




*The 88-Inch Cyclotron: A one-stop facility for electronics radiation and detector testing. M.Kireeff-Covo *et al.*,. Measurement, 127, (2018), p. 580-587.https://doi.org/10.1016/j.measurement.2017.10.018 .

# REBCO and BSCCO Irradiation "Volunteers" at the 88-Inch cyclotron (20 hours @ a total integrated charge of 0.2 Coulomb)



Abby Lee (GS) | Elan Park-Bernstein (UG) | Chris Reis (GS) | Lee Bernstein | Andrew Voyles (Staff)



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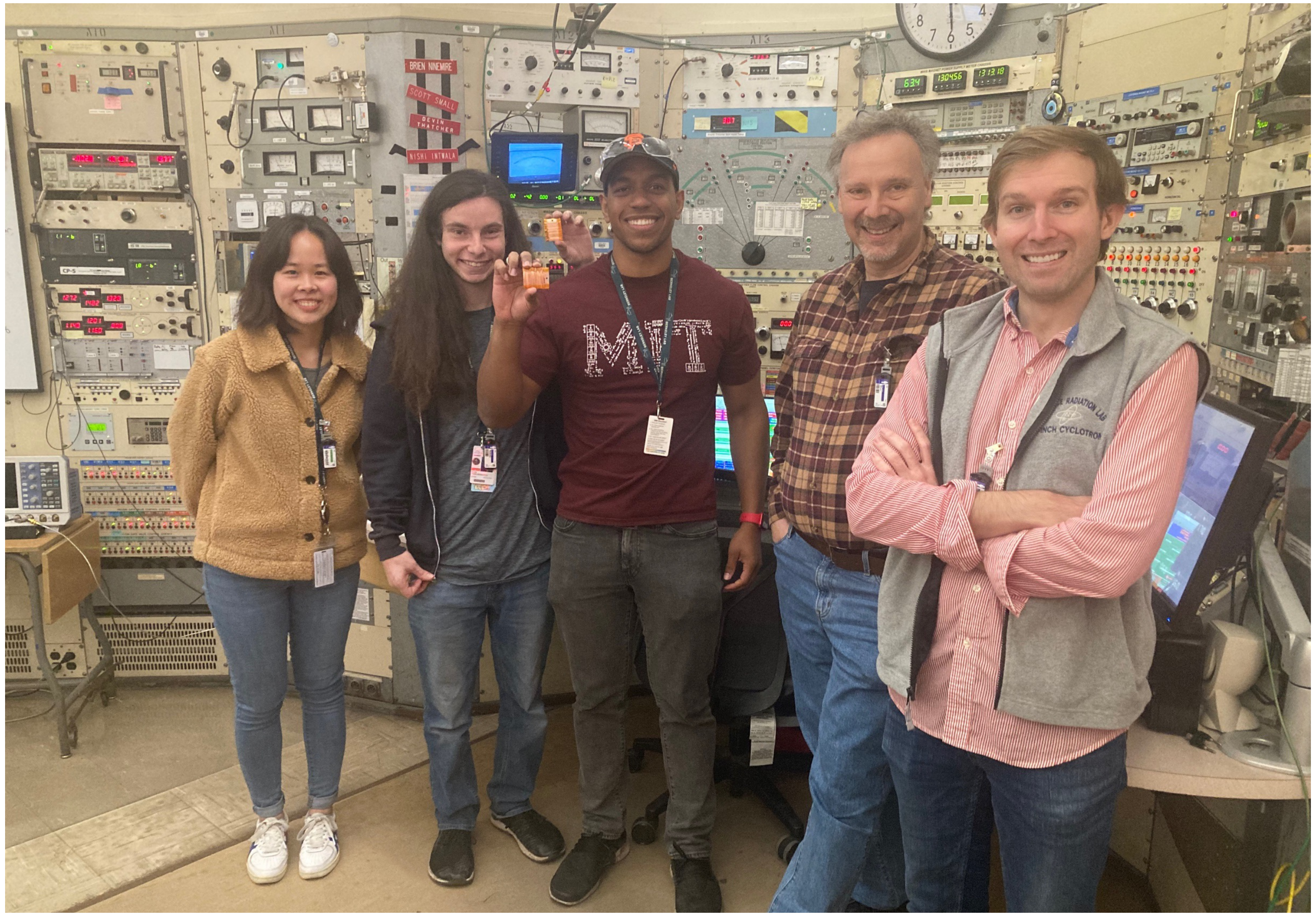

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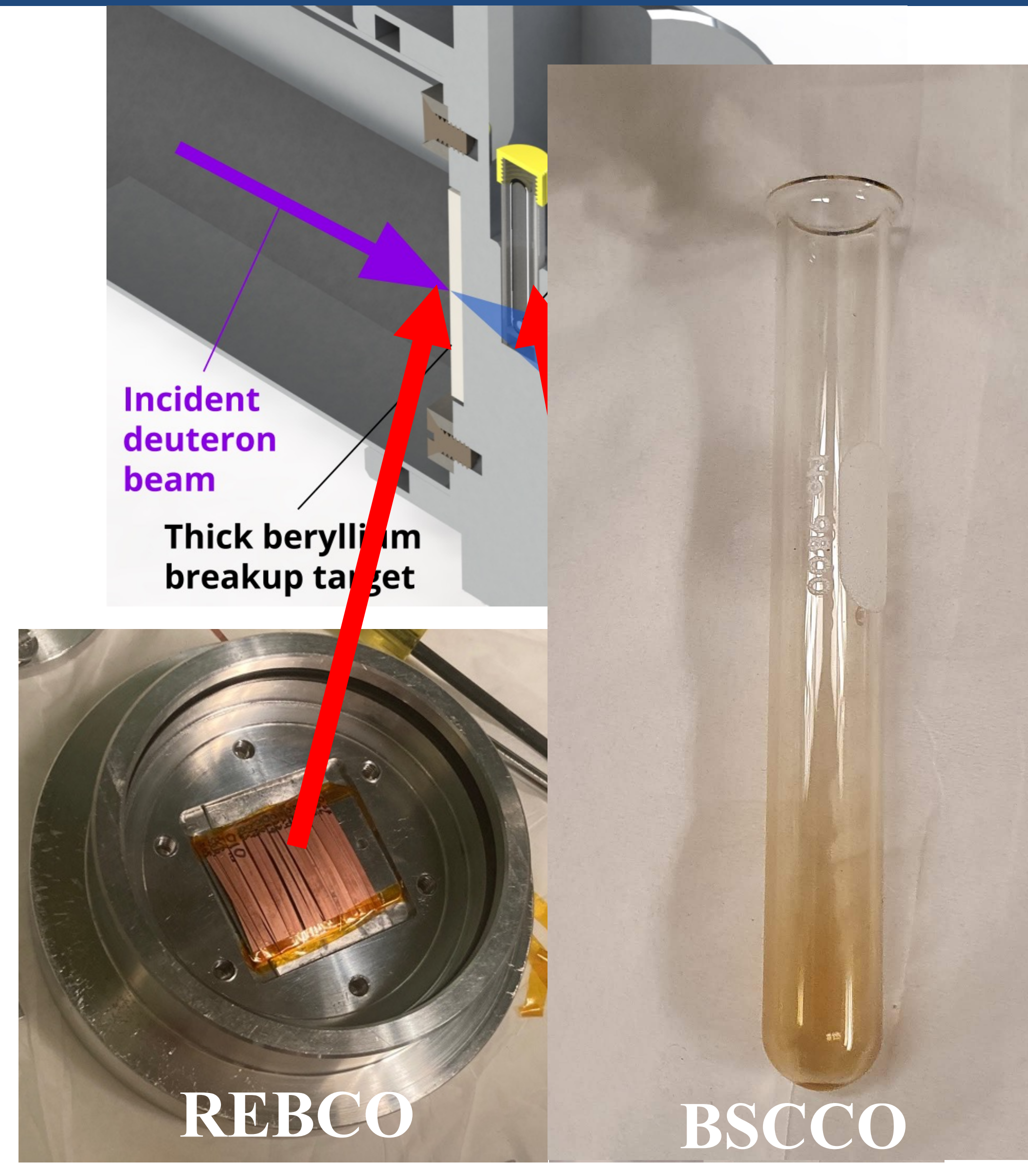
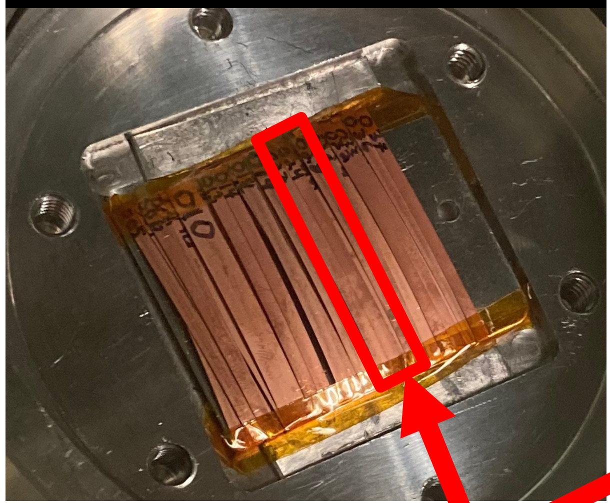
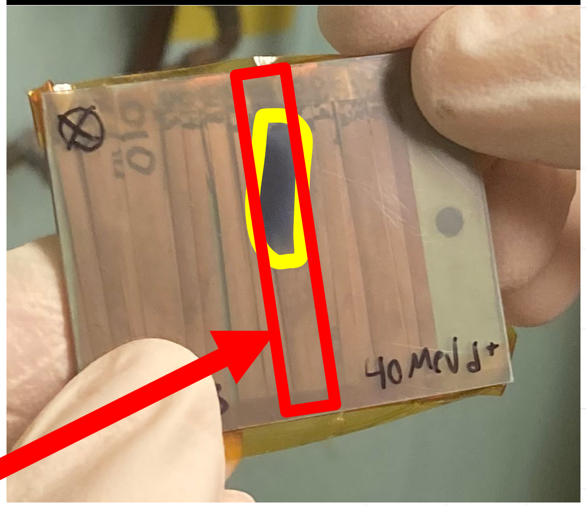


# There is significant variation in flux across the different REBCO strips due to their proximity to the deuteron beam

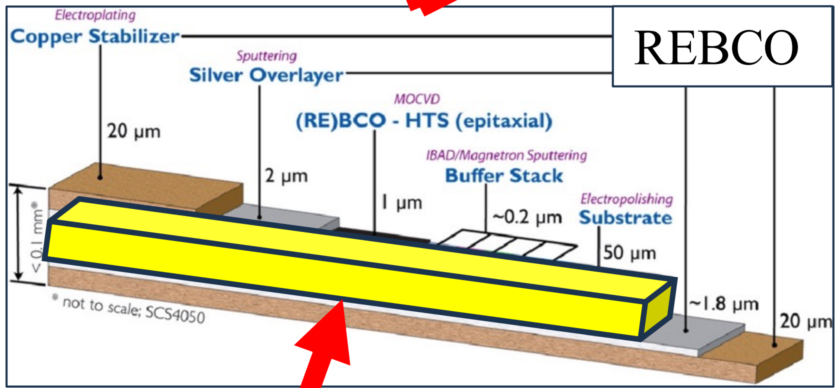
REBCO Strips in HEIFER



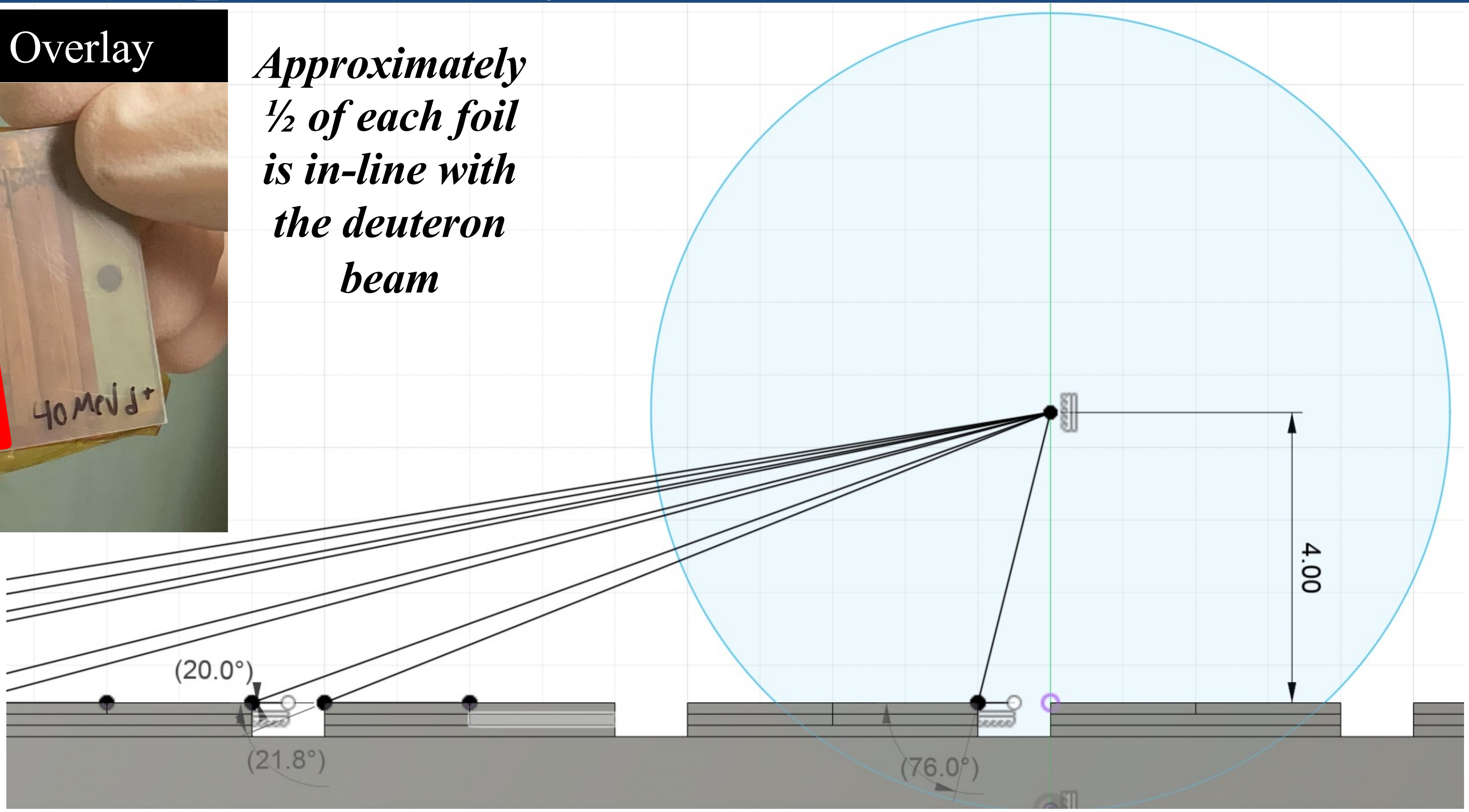
Gafchromic Overlay




***Approximately ½ of each foil is in-line with the deuteron beam***

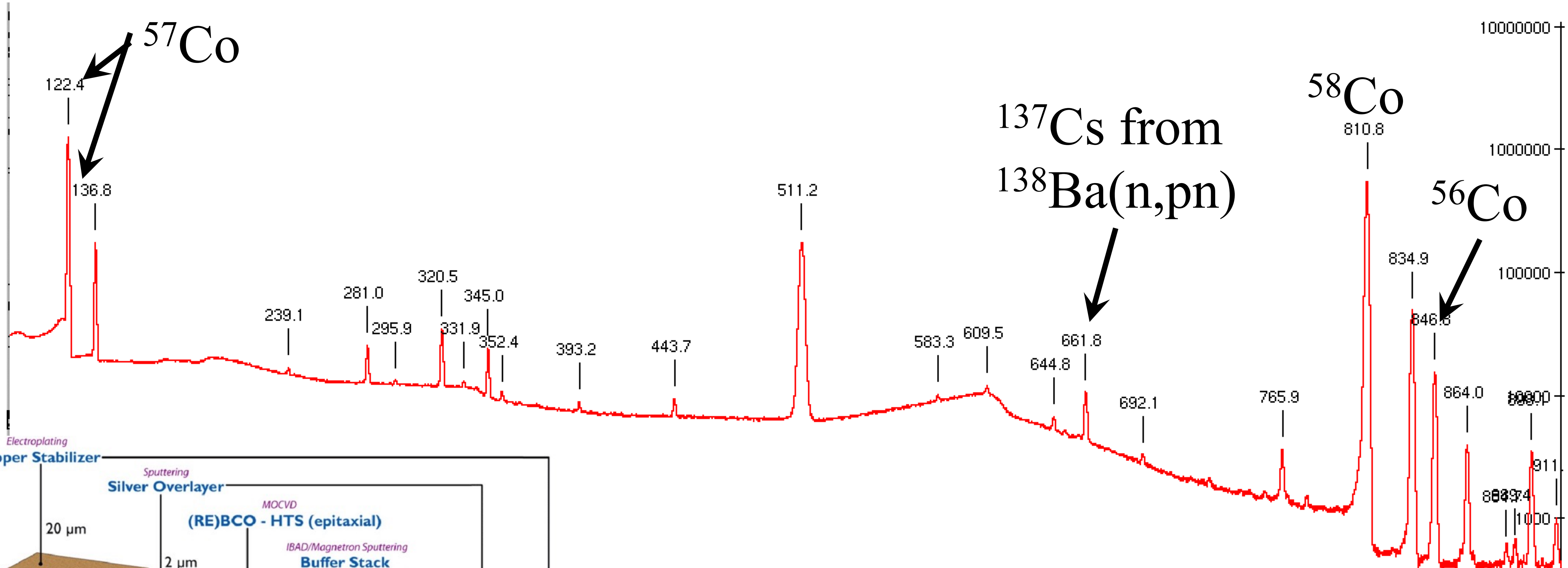


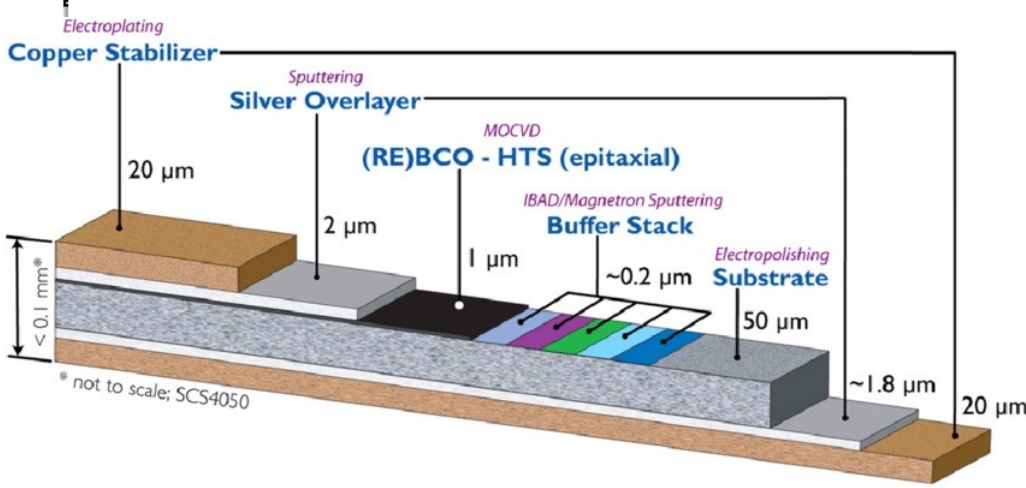

Hastelloy (mostly Ni)



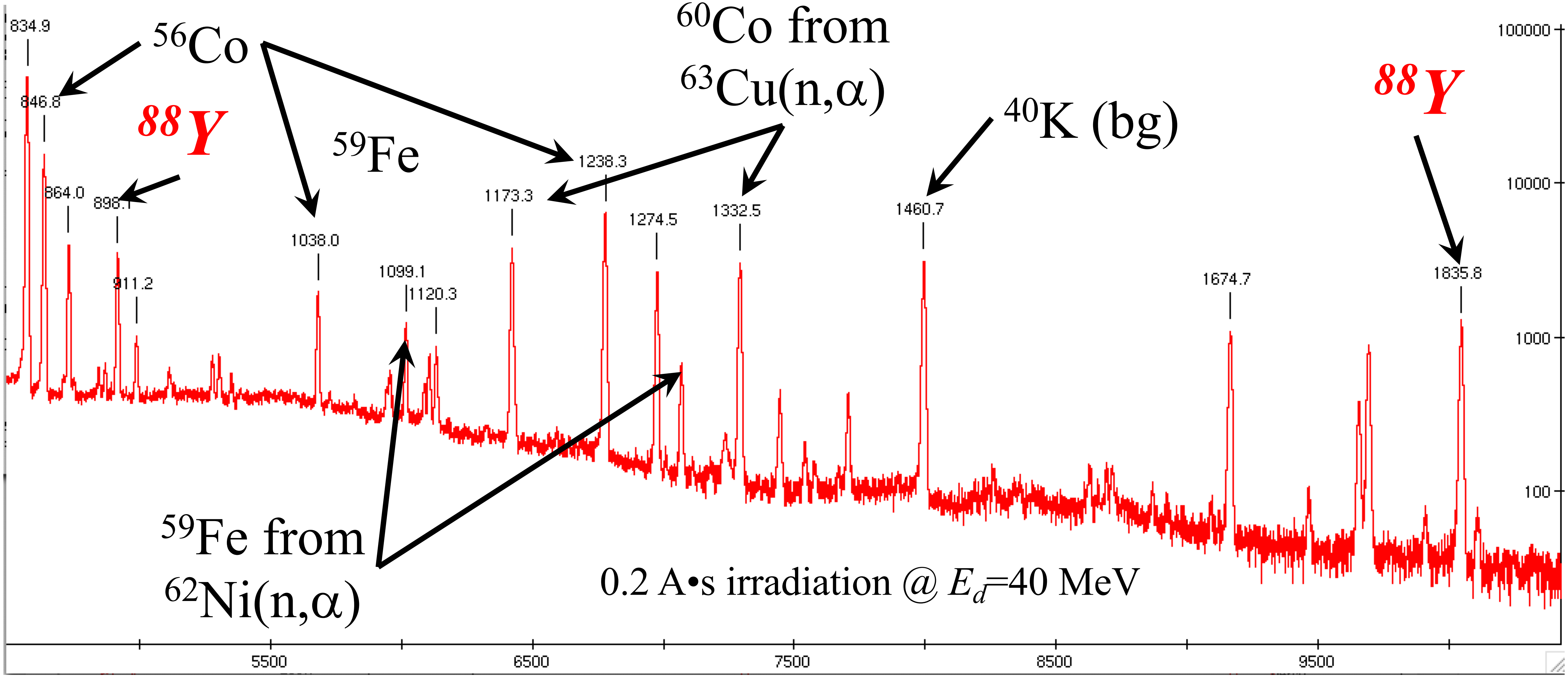

Elan is developing a Monte-Carlo integration code to calculate the spectrum over each REBCO strip

# REBCO Low Energy (14° < θ < 68°)



# REBCO Low Energy (14° < θ < 68°)

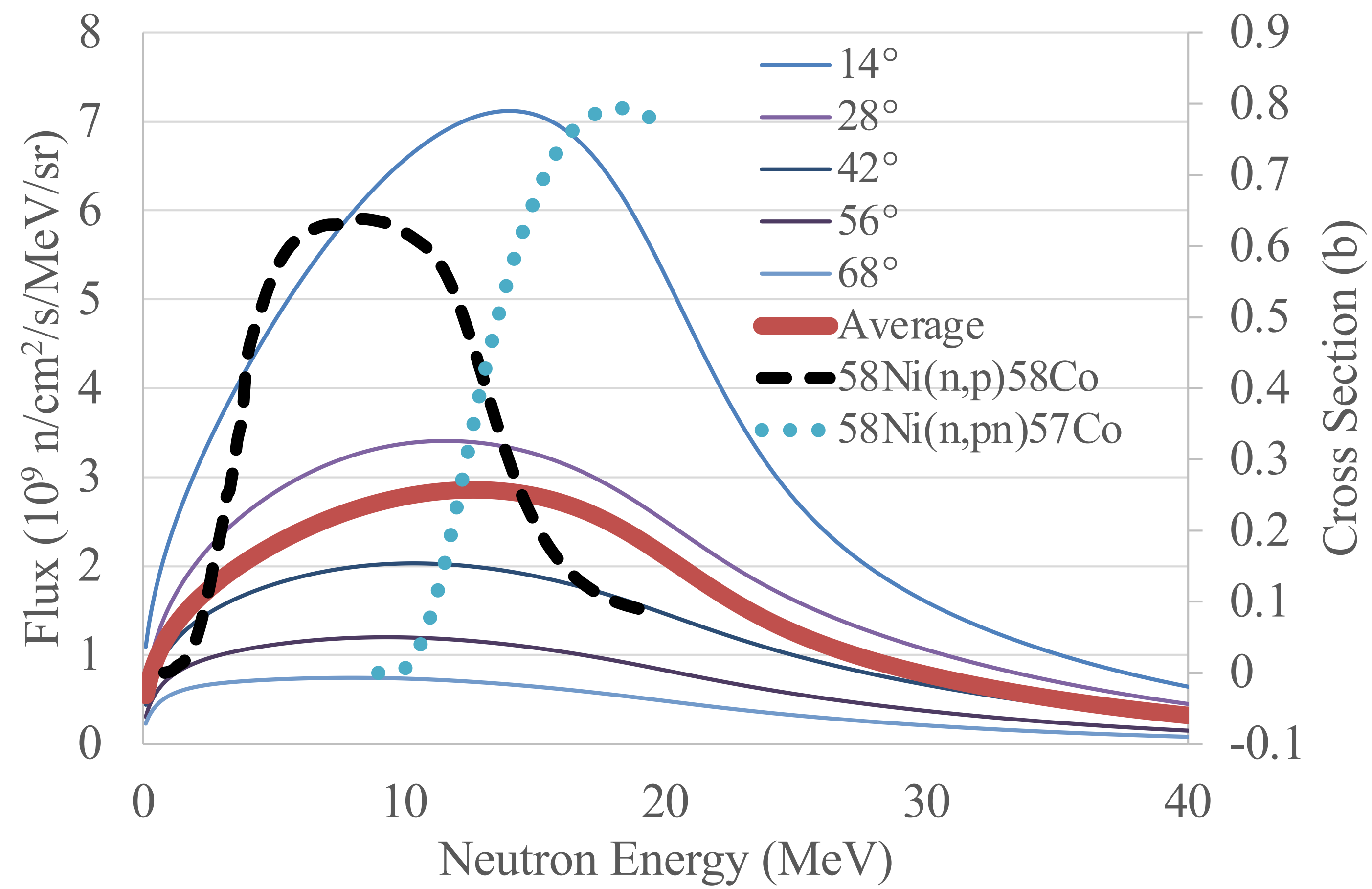


# How do our measured conversion fractions compare to predictions from our neutron model?

- Can assay H production from $^{56-58}Co$
  ***(n,p) data above 20 MeV is essential***
- He production can be calculated
- IFMIF & FPNS use 40 MeV deuterons
  ***This energy might be too high!***

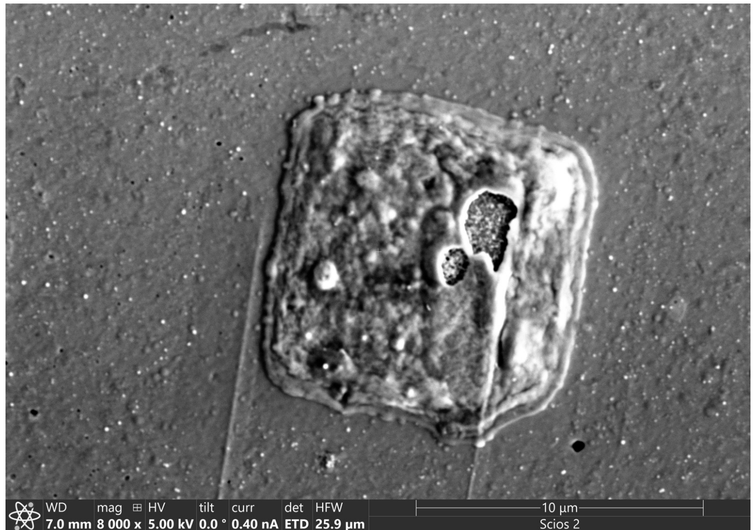
***VERY Preliminary !!!***

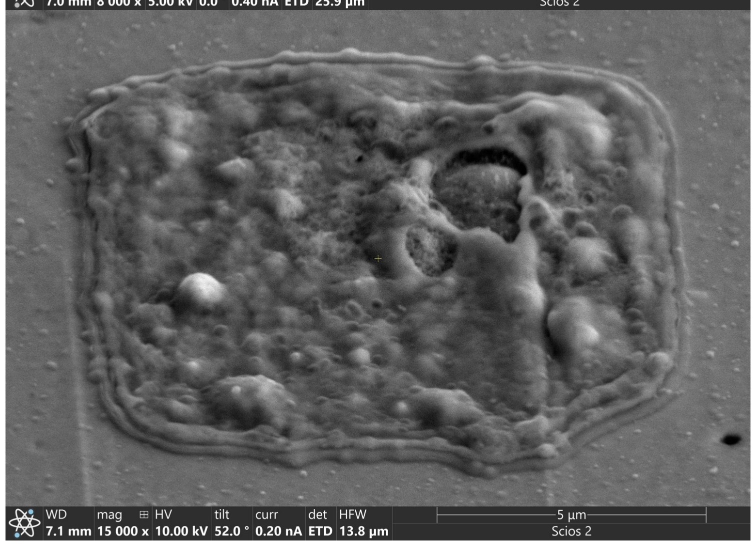
| $\theta_1$ | $\theta_2$ | $^{56}Co$ (x1000) ppb | $^{57}Co$ (ppb) | $^{58}Co$ (ppb) |
|---|---|---|---|---|
| 80 | 81 | 0.68 | 0.04 | 0.12 |
| 76 | 79 | 1.34 | 0.07 | 0.19 |
| 79 | 80 | 1.16 | 0.06 | 0.16 |
| 70 | 75 | 2.68 | 0.14 | 0.34 |
| 14 | 68 | 61.52 | ***1.72*** | ***2.12*** |
| **ENDF + Simple Geometry** | | | ***1.46*** | ***1.81*** |

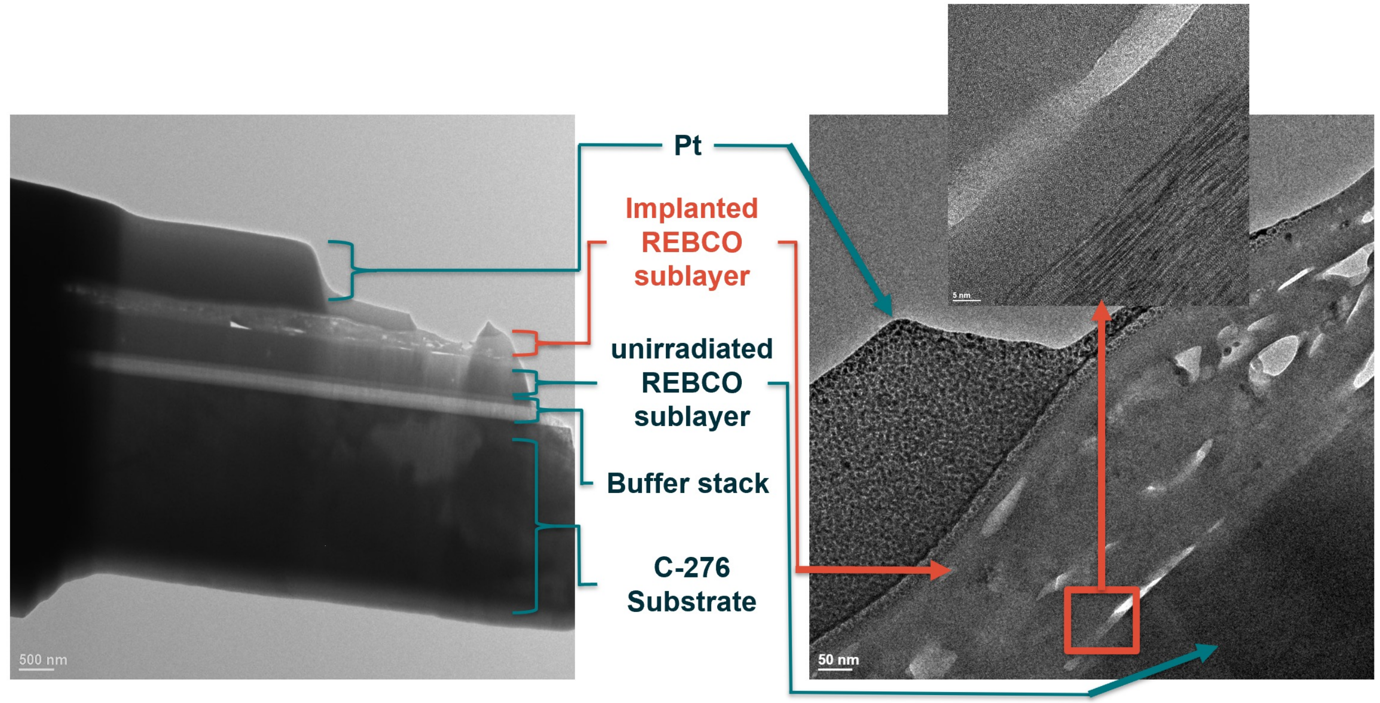



***Similar values (0.7 ppb) were seen in the BSCCO from $^{107}Ag(n,2n)^{105}Ag$***

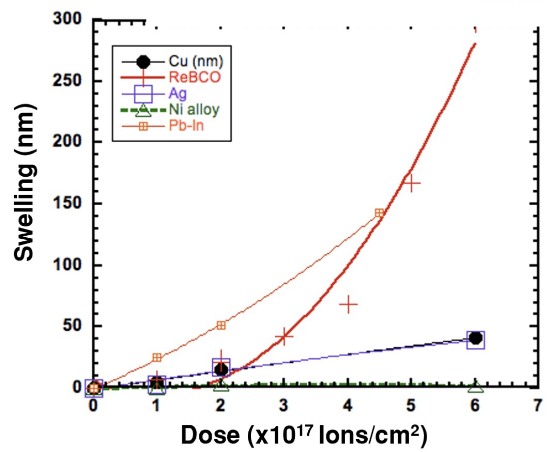
# Chris Reis is spearheading Gas Production/Materials Characterization at UC Berkeley with Hosemann Nuclear Materials Group and LBNL's Molecular Foundry

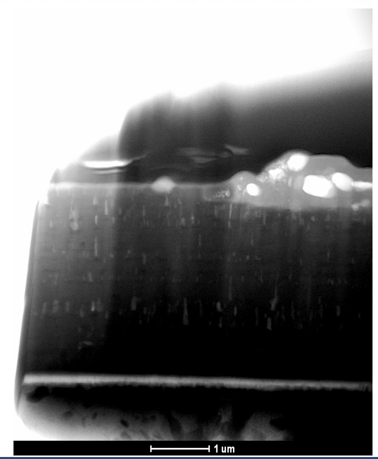


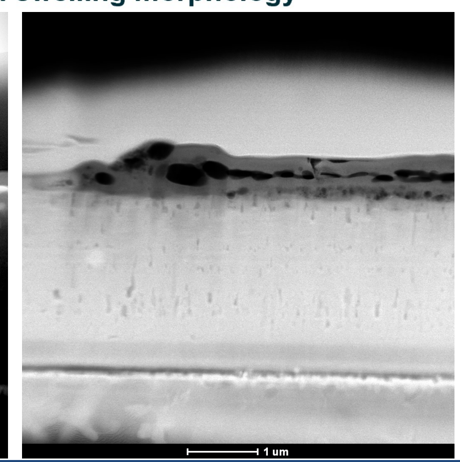




HRTEM of REBCO revealed novel swelling morphology



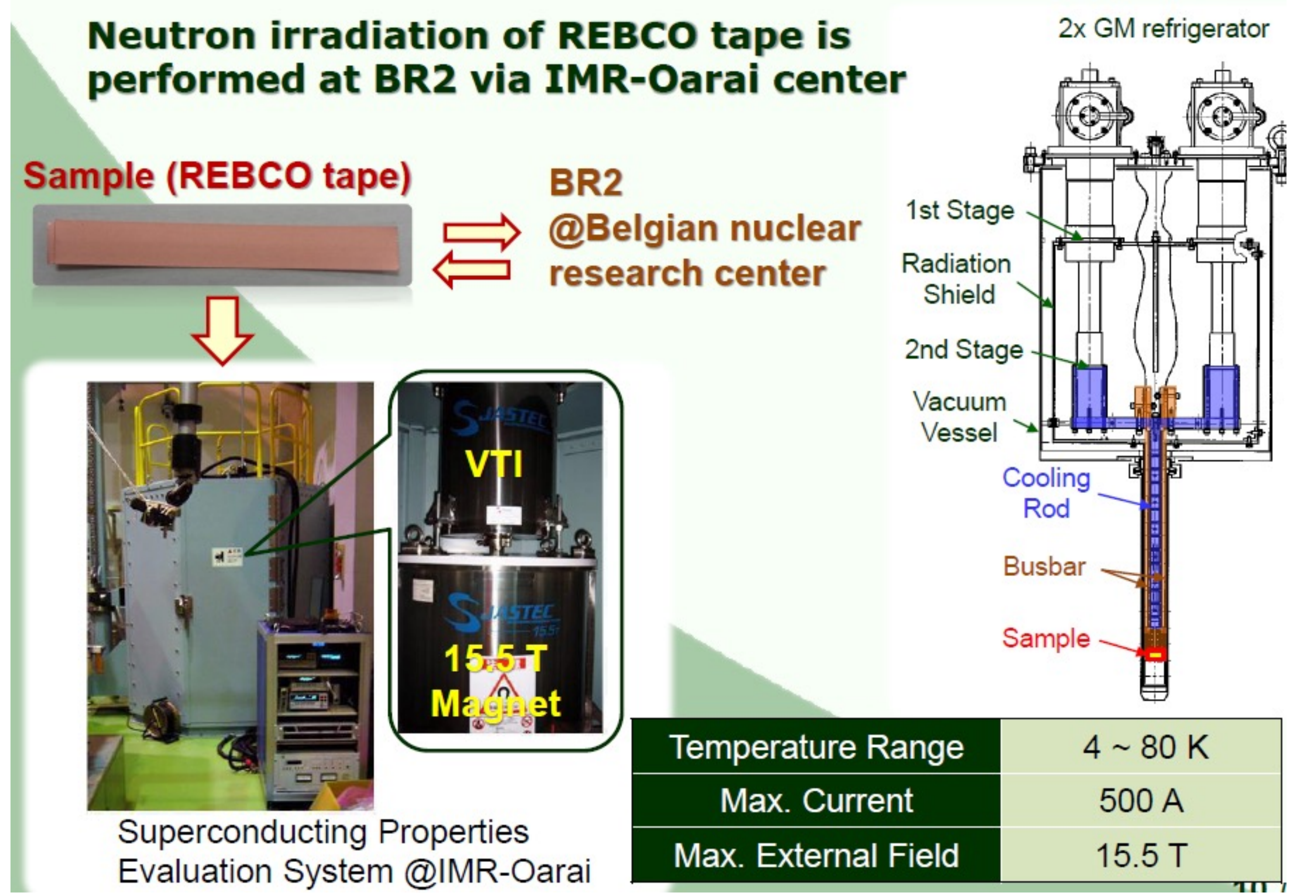


MOLECULAR FOUNDRY

*Work at the Molecular Foundry was supported by the Office of Science, Office of Basic Energy Sciences, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.*

# US-Japan High Energy Physics Collaboration to aid with superconductivity measurements using VTI Probe at IRCNMS

- US-Japan HEP collaboration LBNL Leads Chris Reis, Tengming Shen, et. al coordinating with KEK collaborators Toru Ogitsu, Masami Iio, et. al to assess radiation effects on superconductivity
- 15.5 Tesla Variable Temperature Insert (VTI) specially designed for hot samples to be used at International Research Center for Nuclear Materials Science (IRCNMS)
- Changes to Critical Current, Critical Temperature, n-value, Irreversibility field, etc., are key parameters to be assayed.




| | |
|---|---|
| Temperature Range | 4 ~ 80 K |
| Max. Current | 500 A |
| Max. External Field | 15.5 T |

BERKELEY LAB
BROOKHAVEN NATIONAL LABORATORY
Members of the US Magnet Development Program

Berkeley UNIVERSITY OF CALIFORNIA
KYOTO UNIVERSITY FOUNDED 1897
KEK

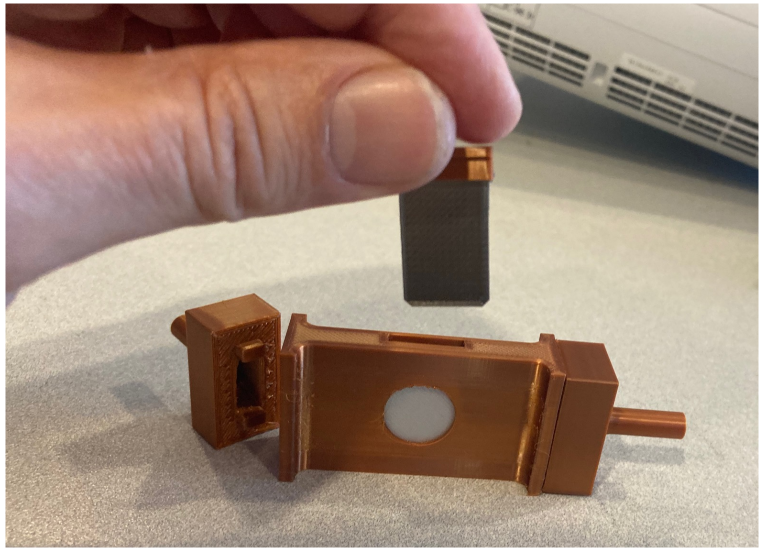
# Conclusions

## Summary

- Several ppb of the Ni in the sample were transformed to Co during a short low-intensity run, making H in the process. Helium production would be similar.
- Lots of Y reactions products (*Is this a big problem?)*
- ***A full scale run (x25 integrated charge at 0°) would yield 0.1-0.2 ppm gas production plus lots of displacements and secondary particle production***

## Future plans

- Perform cryogenic (LN) irradiations using a new jig being designed by the Hosemann/Prestemon group
- Test a new high-intensity Beryllium target developed with a corporate partner (NorthStar)
- Irradiate NIF final stage optics as part of the new IFE-STARFIRE collaboration



# Collaborators and Acknowledgments


Mehul Nair

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*[1]University of California – Berkeley Department of Nuclear Engineering*

*[2]Lawrence Berkeley National Laboratory*


Peter Hosemann


Tengming Shen

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Soren Prestemon


Chase Gesteland